The role of fission in the r-process nucleosynthesis

Aleksandra Kelić
GSI - Darmstadt

Together with:
Karl-Heinz Schmidt, Karlheinz Langanke
GSI - Darmstadt

Nikolaj Zinner
University of Århus - Århus
Motivation

S. Wanajo et al.,
NPA in print

- Fission could have influence on the $A_{\text{max}}$ of the r-process as well as on the yields of transuranium elements and, consequently, on the determination of the age of the Galaxy and the Universe [1]. In cases where high neutron densities exist over long periods, fission could also influence the abundances of nuclei in the region $A \sim 90$ and 130 due to the fission cycling [2,3].

What do we need?

• What are the needed ingredients?
  - Fission barriers
  - Mass and charge division in fission
  - Fission dynamics

• Importance of nuclear structure at large deformations

• And all this for heavy, very neutron-rich nuclei

Covered in this talk
How well can we describe fission?

⇒ Empirical systematics
   - Problem is often too complex

⇒ Theoretical models
   - Way to go!
   - But, not always precise enough and still very time consuming
   - Encouraging progress in a full microscopic description of fission:
     → H. Goutte et al., PRC 71 (2005) 024316
     → J.M. Pearson and S. Goriely, NPA in print

⇒ Semi-empirical models
   - Theory-guided systematics
Saddle-point masses
Open problem

Limited experimental information on the height of the fission barrier

I. Panov et al., NPA 747 (2005) 633
Predictions of theoretical models are examined by means of a detailed analysis of the isotopic trends of ground-state masses and fission barriers.

\[
\delta U_{sad} = E_{f}^{\text{exp}} + M_{\text{exp}} - (M_{\text{macro}}^{\text{macro}} + E_{f}^{\text{macro}})
\]

Experimental saddle-point mass  
Macroscopic saddle-point mass

M. Dahlinger et al., NPA376 (1982) 94
1.) **Droplet model** (DM) [Myers 1977], which is a basis of often used results of the Howard-Möller fission-barrier calculations [Howard&Möller 1980]

2.) **Finite-range liquid drop model** (FRLDM) [Sierk 1986, Möller et al 1995]

3.) **Thomas-Fermi model** (TF) [Myers&Swiatecki 1996, 1999]

4.) **Extended Thomas-Fermi model** (ETF) [Mamdouh et al. 2001]

W.D. Myers, „Droplet Model of Atomic Nuclei”, 1977 IFI/Plenum
A. Sierk, PRC33 (1986) 2039.
W.D. Myers and W.J. Swiatecki, PRC 60 (1999) 0 14606-1
A. Mamdouh et al, NPA 679 (2001) 337
Results

Slopes of $\delta U_{sad}$ as a function of the neutron excess

$\Rightarrow$ The most realistic predictions are expected from the TF model and the FRLD model.

$\Rightarrow$ Inconsistencies in the saddle-point mass predictions of the droplet model and the extended Thomas-Fermi model.
Mass and charge division in fission
Measured fission-fragment Z distributions

Experimental survey by use of secondary beams of radioactive isotopes

K.-H. Schmidt et al., NPA 665 (2000) 221
Macroscopic-microscopic approach

- Transition from single-humped to double-humped explained by macroscopic (fissioning nucleus) and microscopic (nascent fragments) properties of the potential-energy landscape near the saddle point.

- For each fission fragment we get:
  - Mass
  - Charge
  - Velocity
  - Excitation energy
Comparison with existing data

Fission of secondary beams after the EM excitation:
black - experiment
red - calculations
Application in astrophysics - first step

A and Z distributions in neutrino-induced fission of r-process nuclei

1. $\nu$-nucleus interaction $\rightarrow$ RPA

2. Deexcitation $\rightarrow$ GSI code ABLA

N. Zinner

How to continue

→ Detailed r-process network calculations (N. Zinner and D. Mocelj)

→ New experimental data
  - Mass AND charge distributions of both fission fragments at different, well defined excitation energies
  - Light particles and gammas emitted in coincidence

     FAIR facility at GSI

→ Close collaboration between experiment and theory
Additional slides
Microscopic approach to fission

→ H. Goutte et al., PRC 71 (2005) 024316

HFB + time-dependent generator coordinate method:

FIG. 14. Theoretical mass distributions (solid lines) are compared with the Wahl evaluations of neutron-induced fission of $^{238}\text{U}$ [24] (dashed lines). Excitation energies of the compound $^{238}\text{U}$ nucleus measured above the barrier are (a) $E = 2.4$ MeV, (b) $E = 1.1$ MeV.
How well do we understand fission?

Influence of nuclear structure (shell corrections, pairing, ...)

M.G. Itkis et al., Proc. Large-scale collective motion of atomic nuclei, Brolo, 1996

K.-H. Schmidt et al., NPA 665 (2000) 221
Comparison with data

How does the model work in more complex scenario?

$^{238}\text{U} + p \text{ at } 1 \text{ A GeV}$
Example for uranium

$\delta U_{sad}$ as a function of a neutron number

A realistic macroscopic model should give almost a zero slope!